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The Display of Visual Information in Mission Command Systems: Implications for Cognitive Performance in the Command Post of the Future

by Jonathan Z. Bakdash and Norbou Buchler

ARL-TR-6544 August 2013

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Aberdeen Proving Ground, MD 21005

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14. ABSTRACT

In a Mission Command System (MCS), the saliency of displayed information is vital for the speed and accuracy of human information processing, underlying fast cognitive task performance with minimal error rates. The visual display of information in a MCS, the Army's Command Post of the Future (CPOF), was evaluated using the Department of Defense Military Standard MIL-STD-1472G (MIL-STD-1472G, 2012). Compared to the military standard, which defines criteria for adequate human performance, the majority of characters and symbols in CPOF are too small, given the visual angle subtended by sizes of characters and symbols based on viewing distance. Also, based on the military standard, nearly half of the elements in CPOF lacked sufficient visual salience (i.e., contrast). To improve reading performance with the visual display in CPOF, the following changes are recommended: (1) Increase the Visual Angle—Implement support in CPOF to change the size of all visual elements, including the font size, to at least 0.25°, and (2) Increase Contrast—Changes to characters and backgrounds are necessary so that all reach a minimum contrast level of 6:1. High contrast can be created with dark characters on a light background or light characters on a dark background.

15. SUBJECT TERMS

Network centric operations; cognitive performance, visual perception, Command Post of the Future

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1. Summary

In a Mission Command System (MCS), the saliency of displayed information is vital for the speed and accuracy of human information processing, because it underlies fast cognitive task performance with minimal error rates. The ability to quickly and accurately process information is necessary for realizing the principal advantage of network-centric mission command that increased information leads to greater mission success by reducing uncertainty in the operational environment. The mere availability of information is not sufficient to achieving information superiority; it can only be achieved if a MCS supports Soldier needs and capabilities.

The visual display of information in a MCS, the Army's Command Post of the Future (CPOF), was evaluated using the Department of Defense Military Standard MIL-STD-1472G (MIL-STD-1472G, 2012). Compared to the military standard, which specifies criteria for adequate human performance, the majority of characters and symbols in CPOF are too small, given the visual angle subtended by the sizes of characters and symbols based on viewing distance. Also, based on the military standard, nearly half of the elements in CPOF lacked sufficient visual salience, that is, the relative difference or contrast which is the difference between foreground and background colors.

Using the military standard as a baseline for adequate performance, a specific measure of cognitive performance (reading speed) was predicted using the visual angle of characters in CPOF. Based on established research on reading performance, CPOF reading performance was estimated to be substantially slower (27% slower for the laptop display and 16% slower for the desktop display) compared to text adhering to the visual angle specifications in the military standard. Poor visual salience of text is likely to produce further deterioration in reading speed and accuracy. Human performance for reading text and symbols can be improved by making changes to visual elements in CPOF to comply with the requirements in the military standard.

To improve reading performance with the visual display in CPOF, the following changes are recommended:

1. **Increase the Visual Angle.** Implement support in CPOF to change the size of all visual elements, including the font size, to at least 0.25° for characters. Ideally, the scaling of visual elements could be independently specified for a monitor by using the pixels per inch of each display device.

2. **Increase Contrast.** Changes to characters and backgrounds are necessary so that all reach a minimum contrast level of 6:1. High contrast can be created with dark characters on a light background or light characters on a dark background.

2. Introduction

CPOF is a widely used collaborative MCS for visualization, information management, and collaboration. The CPOF tools support monitoring, planning, and mapping of the operational environment by the mission command staff whose work products can be "subscribed to" and rapidly shared across the network (Greene et al., 2010). CPOF works to leverage a principal advantage of network-enabled mission command: the notion that more robust information sharing leads to greater mission success by reducing uncertainty and acts as a force multiplier (Alberts et al., 2000). Attaining information superiority requires high performance from technical systems (e.g., sensors, network connectivity and bandwidth, and the information systems, such as the MCS). However, the high performance of technical systems alone is not sufficient for mission success. If Soldiers cannot quickly and accurately process information, more information may actually be detrimental rather than beneficial to mission success (Cummings et al., 2010). Soldier capabilities and needs must be supported by MCS. In an information-rich environment, reading speed is an important dimension of cognitive performance: the premise of network-enabled operations requires that humans, and also technical systems, can quickly and accurately process large amounts of information.

In a MCS, the display of information is crucial for speed (the rate of human information processing, e.g., number of words read per minute) and accuracy because it is a key primitive for fast and safe, error-free cognitive performance. The visual display of information in an MCS, the Army's CPOF, was evaluated. Specifically, the size of visual elements and visual salience of elements were compared to the Department of Defense Military Standard MIL-STD-1472G (MIL-STD-1472G, 2012). The majority of evaluated CPOF visual elements failed to meet the military standard, which provides criteria for adequate human performance. Using the size of text in CPOF, the impact for a particular measure of cognitive performance (reading speed) was inferred using a previously published psychophysical function of reading performance for text of different sizes (Legge et al., 1985).

Although reading is just one measure of the rate of human information processing, it is fundamental to cognitive performance with a MCS. For a MCS, reading is relevant to using the software interface, the names of locations on a map, and alphanumeric identifiers for friendly and enemy units. Typically, reading is a highly automatic cognitive process, but impoverished visual information, such as text that is too small and poor saliency (i.e., dark text on a dark background or light text on a light background), increases the time needed to read information and raises error rates (Legge, 2007). In CPOF, the resulting negative implications for reading performance because of the low adherence to specific visual aspects of the MIL-STD-1472G

Standard (size and salience), together, strongly suggest the need for improvements to the size and saliency of visual elements in CPOF.

Moreover, the negative impact on cognition for poorly displayed visual information is not limited to reading performance. On tasks where human perception is relevant to performance, degraded visual information makes reading less of an automatic process by increasing the reliance on other stages of cognition: memory, decision-making, and attention (Norman, 2002). To conceptualize the stages of cognition and the relationships between stages of cognition, a generic information processing model of human cognition (Simon, 1979; Wickens and Flach, 1988) is shown in figure 1.

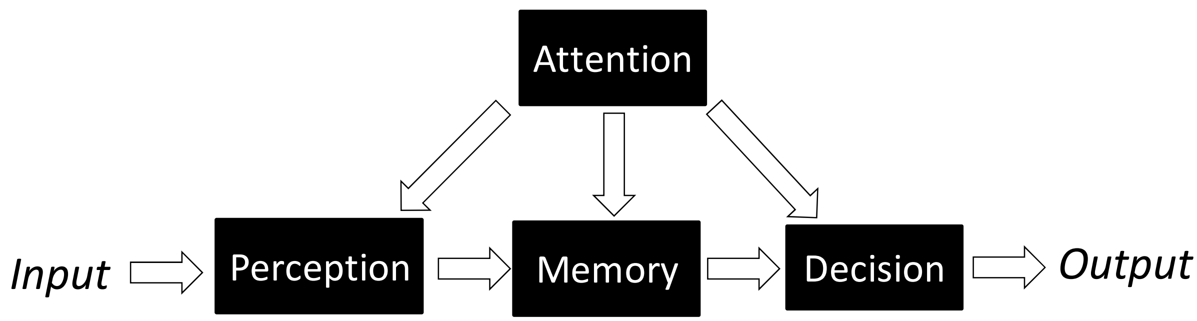

Figure 1. Information processing model of human cognition.

In this generic model of human information processing, the inputs are the available information, in our case this consists of visual elements in CPOF. Black boxes represent the four stages of cognition. Attention is connected to perception, memory, and decision-making. The output is typically executing a response or completing a task or subtask. Here, the output is reading because that is the information that is being processed.

Memory, decision-making, and attention should be preserved, as much as possible, for tasks more complex than reading, for example the understanding of future threats, proactive decision-making with respect to capabilities, and expression and comprehension of command intent (Alberts, 2006).

2.1 Network-Enabled Operations

A major goal in network-enabled operations is to achieve a dramatic improvement in mission command staff collaborative decision-making in the presence of large volumes of time critical information. CPOF was designed to support the Army transformation to network-enabled operations. The transformation has proceeded under a conceptual framework and a strategic concept that possesses four main tenets (Alberts and Garstka, 2004):

- A robustly networked force improves information sharing and collaboration.
- Such sharing and collaboration enhance the quality of information and shared situational awareness.

- This enhancement, in turn, enables further self-synchronization and improves the sustainability and speed of command.
- The combination of the above three dramatically increases mission effectiveness.

CPOF supports the tenets of network-enabled operations by providing the building blocks for information management, sharing work products, and collaborative decision-making across the mission command network. It does so by using networked information visualization systems with shared workspaces that serve as the main interface. Each interface element in CPOF is a shared piece of data in a networked repository. Shared interfaces in CPOF include many visual elements: iconic representations of hard data, such as units, events, and tasks; visualization frames, such as maps or scheduling charts on which those icons appear as configurable overlays; and other features, such as highlighting (digital pen), note taking "stickies," and annotations. Visualization of data is a central feature to many of the collaborative products that can be developed and shared in the CPOF software environment.

2.2 Past CPOF Research

Previous research on CPOF consisted of the following:

1. Technical system evaluations and a human factors assessment using self-report data (interview comments and survey data). The technical research includes Manpower and Personnel Integration (MANPRINT) system evaluations.
2. Identification of the critical skills to use the CPOF interface and CPOF skill retention.

Middlebrooks (2008) conducted a human factors evaluation of CPOF. This evaluation was a general assessment of human factors issues with CPOF, identifying problems based on qualitative comments from Soldier interviews and survey data using questionnaires. The current report is narrower in scope than Middlebrooks (2008); it is an evaluation of the visual display of information in CPOF and the implications for one measure of cognitive performance as in reading. In contrast to the MANPRINT evaluations, the purpose of this report is a preliminary effort to assess the visual display of text and other information in safety critical software systems. Hence, this report has implications for the visual display of information in prototype and production MCSs. Other MANPRINT assessments have been conducted for MCSs (Middlebrooks, 2006a), and human factors evaluations of MCSs (Middlebrooks, 2006b).

Catarambone et al. (2009) used a task analysis with expert CPOF users to determine the critical skills needed to use the CPOF interface, for example the steps for creating an event in CPOF. Related to determination of skills, retention of CPOF critical skills was assessed after 24 h of CPOF training and five weeks later (Bink et al., 2011). Retention was absent in half of the CPOF critical skills, although the effect sizes for skill loss appear quite small. These reports illustrate the essential skills needed to use the CPOF interface but do not explicitly address the visual display of information in CPOF.

2.3 Visual Displays and Cognitive Performance

The visual display of information is vital to cognitive performance. For example, the poor visual design of the radar display on the USS Vincennes was a major cause* of an accident in which a passenger aircraft was erroneously identified as an attacking enemy aircraft and shot down (Wickens et al., 1998). In this incident, visual information on the radar display was processed slowly and inaccurately by humans. Critical information (aircraft location, the alphanumeric identifier for the aircraft, its altitude, its heading, and its speed) was spatially positioned in different locations of the screen; the text was too small making the information difficult to find and read, and the availability of some of this information varied by the view selected on the radar (Klein, 1996; Wickens et al., 1998). The radar display required effortful cognitive processing: information could not be perceived directly; it had to be found, which created a high dependence on memory, decision-making, and attention.

Inadequate visual displays are also associated with human error in other safety critical domains: health care and nuclear power plant operation. In health care, the switch to labels for prescription medications with large fonts, simplified language, and pictorial warnings has reduced medication errors for clinicians, pharmacists, and patients (Horsky et al., 2005; Morrow et al., 2005). Although medication labels are not an electronic visual display, they are still a display of visual information. Like the USS Vincennes, the example with medication labels also exemplifies limitations in human information processing, which are exacerbated in a suboptimal operational environment. As in the military domain, health care is often characterized as a suboptimal operational environment, that is, error-producing conditions due to stress, time pressure, fatigue, understaffing, and lack of training (DeLucia et al., 2009). Also, many of the visual displays used to operate nuclear power plants lag behind standards in human factors, and the inability for human operators to rapidly and accurately process the visually displayed alarm information has been linked to accidents (Carvalho et al., 2008). A clear presentation of visual information is essential to minimizing error, because it promotes automatic cognitive processing, rather than burdening humans with work-arounds, such as decreasing viewing distance to the display, and excessive dependence on memory and attention because information cannot be processed automatically.

* There were a multitude of factors that contributed to the accident, as is typical of "human error" (Reason, 1990). In an accident with the USS Vincennes, multiple factors included time pressure, stress, inexperience with combat, lack of equipment training, breakdowns in communication, and the expectations created by operating in a hostile environment (Klein, 1996). Nevertheless, the visual radar display was a major casual factor, because it made the processing of information cognitively effortful in terms of finding, integrating, and understanding the aircraft location, direction of altitude changes, and even the alphanumeric sequence identifying the aircraft (Wickens et al., 1998).

2.4 Automatic and Controlled Processing

For sufficient cognitive performance, human factors standards and principles for visual displays generally promote automatic processing of information (Norman, 2002; Shneiderman, 2003; Wickens et al., 1998). Norman (2002) calls automatic processing "knowledge in the world," visual information that can be directly perceived, in contrast to "knowledge in the head," which heavily draws on cognitive resources other than perception (memory, decision-making, and attention). Using the radar display on the USS Vincennes imposed knowledge in the head: memorization of altitude readings, decisions based on memory, and attending to and searching for visual information in different spatial locations. Visual information that can be perceived directly without inferences (Gibson, 1979) is a form of automatic processing.

Automatic and controlled information processing can be more formally distinguished (Shiffrin and Schneider, 1977). Automatic processing is fast; it is primarily perceptual with a minimal dependence on other stages of cognition (Shiffrin and Schneider, 1977). In comparison, controlled processing is mentally effortful with a strong dependence on cognitive resources other than perception (memory, attention, and decision-making) and is slower (Shiffrin and Schneider, 1977). The radar display on the USS Vincennes required controlled processing of basic visual information (e.g., aircraft location and identification, and aircraft altitude changes) because of the poorly designed display, which cognitively burdened the radar operators. Likewise, impoverished visual information in health care (e.g., a difficult to read medication label) also increases the dependence on memory and attention, resulting in a greater likelihood of error (Morrow et al., 2005).

This is not to say automatic processing is always better than controlled processing; it depends on the task. In situations with degraded or partially hidden visual information, controlled processing is ideal (Wickens et al., 1998). For example, in a visual search task to detect rarely present targets, performance can be improved by giving users the option to take a second look after their initial response of target present or target absent (Fleck and Mitroff, 2007). This example is analogous to threat detection with baggage screening or anomalies in medical imaging. However, the visual information displays in an MCS should support automatic human processing of visual information. An additional benefit of automatic processing of visual information is the preservation of other cognitive resources (memory, decision-making, and attention) for more complex cognitive operations.

2.5 Cognitive Performance

In this report, objective cognitive performance is predicted for reading. There are other types of objective metrics of cognitive performance, which are also relevant for using an MCS. These other metrics can be generally expressed as measure of speed and accuracy and vary by the task and stage(s) of cognition being assessed. For example, if a chat report of a potential improvised explosive device comes in, how long does it take the Soldier to read information and make a decision, was the decision optimal, how long did it take to update the relevant information in an

MCS, and was the threat communicated to the appropriate individuals? Consequently, the above objective measures of cognitive performance tend to be higher-level than reading performance.

Other more specific measures, which are lower-level objective measures of cognitive performance include the following:

1. Eye-tracking (indicator of the allocation of attention) (e.g., Yarbus, 1967)
2. Mouse logging, which is a proxy for eye-tracking (e.g., Chen et al., 2001; Cooke, 2006)
3. Goals, operators, methods, and selection (GOMS): A computational modeling approach, which simulates stages of cognition and can be used to compare different software interfaces and identify areas where performance breaks down (John, 1995).

The use of objective measures is paramount for any domain or system that is safety critical. In contrast to subjective measures (e.g., self-report data, such as user juries, user preferences, focus groups, and observational ratings), objective metrics capture actual cognitive performance (Andre and Wickens, 1995). Subjective measures tend to be broader and may provide insight into general problems that negatively impact cognitive performance and specific user needs, such as work flow and task requirements. However, because subjective measures are self-reported, they can and do differ from actual, objective performance. Hence, the focus here is on objective measure of cognitive performance, specifically, reading performance. The importance and assessment of cognitive performance in mission command is summarized in Bakdash (2012).

3. Methods

The comparison of the CPOF visual information display with the MIL-STD-1472G Standard entailed measuring the visual angle and contrast:

1. *Visual angle:* Size of text and symbols based on display specifications (display size and resolution) and the maximal viewing distance (preferred viewing distance covering 95% of the population), per the MIL-STD-1472G Standard
2. *Contrast:* Visual salience of elements based on their color and the color of the background

In section 3.1, the formal definitions and the formulas for visual angle and contrast are explained. In section 3.2, the specifications of the visual displays used in CPOF and values used for the viewing distances are covered. In section 3.3, a summary of the relevant aspects of the MIL-STD-1472G Standard is provided. Version BC 10.0.1 of CPOF was evaluated. Because CPOF has large number of menus and functions, only the visual characteristics of major elements were assessed.

In addition to the comparison with the MIL-STD-1472G Standard, reading performance for text in CPOF was estimated based on the visual angle using a psychophysical function of performance from Legge et al. (1985). The reason for predicting reading performance is to illustrate the negative consequences, for cognitive performance, with failures to adhere to the military standard. Due to the complex relationship between visual angle and contrast for reading performance, it was not possible to infer the impact of contrast on reading performance. Previous research has shown that reading speed and accuracy are impacted by the visual angle of text (Legge, 2007). Reading speed for text in CPOF was predicted using the following:

1. Calculating the visual angle of characters for the laptop and desktop displays used in CPOF, based on the display specifications and maximal viewing distance. Per the MIL-STD-1472G Standard, the maximal viewing distance was used in the calculation of visual angle. The maximal viewing distances were derived from the upper-bound values determined in past empirical research on the display viewing distance preferences, which covered 95% of the population.

2. The visual angle for the MIL-STD-1472G Standard as an adequate level of performance.

3. Using a psychophysical function of reading speed (Legge et al., 1985) to compare performance for the actual visual angles in CPOF versus the visual angles specified by the MIL-STD-1472G Standard.

3.1 Visual Angle and Contrast: Definitions and Formulas

Cognitive performance, reading speed here, for the display of visual information is constrained by human capabilities (Palmer, 1999; Proffitt, 2006). The ability to discriminate between patterns of perceptual information is called *visual acuity*, for example discriminating between a "C" and an "O" (Thompson et al., 2011). Object size (e.g., text) and viewing distance together provide enough information to calculate the visual angle (Thompson et al., 2011):*

$$\alpha = \tan^{-1}\left(\frac{D}{I}\right), \quad \alpha = \text{visual angle, } D = \text{viewing distance, and } I = \text{height} . \tag{1}$$

The visual angle is preferable to a measure of physical size (e.g., inches, centimeters, or typographic metric, such as points) because it reflects viewing distance (Legge and Bigelow, 2011). In addition, the visual angle is sometimes expressed in minutes of arc. The conversion from degrees into minutes of arc is 1° = 60 min of arc (Legge and Bigelow, 2011).

Note that Legge et al. (1985) use the visual angle for *character width*, as opposed to *character height*. Character height was used here to make figures 3−7 easier to read and because the military standard uses height, not width. The conversion is straightforward: height can be converted to width using a ratio of 0.9 (MIL-STD-1472G Standard, 2012, 5.2.2.4.1, f.). This

* The formula for calculating the visual angle can also be approximated as visual angle (degrees) = 57.3 × (physical size/viewing distance) (Legge and Bigelow, 2011).

conversion makes no difference; the results are equivalent with direct measurements of character width.

For visual salience, *contrast* and *color* are defined next. *Contrast* is the relative difference in the luminance values, the intensity of light for one element compared to another element two elements (Palmer, 1999). High contrast increases visual acuity by making edges more salient. The highest possible contrast is black text on a white background, or vice-versa. The formula for the contrast ratio (Thompson et al., 2011)* is

$$\text{Contrast Ratio} = \left(\frac{\text{Maximum Luminance}}{\text{Minimum Luminance}}\right). \tag{2}$$

Color is related to contrast because colors vary in both physical and perceived intensity (Palmer, 1999). For example, blue text on a blue background has a low contrast ratio because the text and background have similar luminance values. The contrast ratio and luminance were calculated using a computer application called *Contrast Analyser* ("Contrast Analyser for Windows and Mac | The Paciello Group," n.d.). The following formula was used to determine luminance for CPOF elements using pixel red−green−blue color values:

$$\begin{aligned} \text{Luminance} = {} & (0.2126 \times \text{ Red Value}) + \\ & (0.7152 \times \text{ Green Value}) + \\ & (0.0722 \times \text{ Blue Value}). \end{aligned} \tag{3}$$

3.2 Visual Display Specifications and Viewing Distances: Definitions and Formulas

For the evaluation, there are three relevant display specifications: physical size, number of pixels, and pixel density. The physical size of a visual display size is typically measured diagonally. The resolution of a visual display is defined by its number of pixels. Using size and resolution, pixel density can be calculated using a unit called pixels per inch (PPI) (sometimes colloquially called dots per inch, which actually refers to printing).

The PPI of a display and the operating system determine the physical size of characters. This can be problematic because characters are much often smaller than a designer intended (Pemberton, 2002). In Microsoft Windows, the default setting is 96 PPI, and Microsoft provides guidelines for scaling on high-resolution displays ("Writing High-DPI Win32 Applications," n.d.). Although few programs support scaling on high-resolution displays, few software applications are safety critical with the exception of health care, aviation, nuclear power plant operation, military domain, etc.

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* There are many methods for measuring contrast (Thompson et al., 2011). In addition, comparing contrast levels between different display devices is not straightforward (Thompson et al., 2011). For the purposes of this report, the display specifications for contrast and color and additional factors (e.g., ambient lighting, matte versus glossy screen, display brightness and contrast) are not considered. Thus, these additional factors are ideal in the calculations, representing a best case scenario for both the viewing conditions and properties of the display.

Without scaling, a display exceeding 96 PPI will have text and other elements that are smaller than intended. For example, a display with 133.19 PPI will have characters that are $\left(\frac{96 \text{ PPI}}{133 \text{ PPI}}\right) =$ 72.18% of their intended physical size. On 220 PPI display,* characters would be less than half of their intended size: $\left(\frac{96 \text{ PPI}}{220 \text{ PPI}}\right) = 43.64\%$. A display with a high-pixel density, without an appropriate scaling mechanism in the application, may lead to impaired cognitive performance simply because of impoverished visual acuity.

The evaluation of CPOF is based on the displays used in multi-monitor setup, a laptop and two to three desktop displays (TBC Client Family, Program Executive Office: Command, Control, Communications: Tactical, April 2011). The laptop displays have a higher pixel density (133 PPI) than the Windows default (96 PPI), whereas the desktop display has a lower pixel density (87 PPI) than the Windows assumed default. Table 1 shows the specifications for the displays used in CPOF.

Table 1. Visual displays used with CPOF.

Display	**Resolution**	**Diagonal Size (inches)**	**Diagonal Size (centimeters)**	**Pixels Per Inch**
Laptops Dell M90 laptop: WUXGA display	1920 × 1200	17	43.18	133.19
Dell M6300 laptop: WUXGA display	1920 × 1200	17	43.18	133.19
Dell M6400 laptop: WUXGA display	1920 × 1200	17	43.18	133.19
Dell M6500 laptop: WUXGA display	1920 × 1200	17	43.18	133.19
Desktop Dell 19" monitor	1280 × 1024	19	48.19	86.53

Note: All laptops have the same display specifications.

To determine the PPI, the number of diagonal pixels was calculated using the Pythagorean Theorem:

$$a^2 + b^2 = c^2. \tag{4}$$

where a = number of horizontal pixels, b = number of vertical pixels, and c = number of diagonal pixels.

* A MacBook Pro is now available with 15.4 in display with a 2880 × 1800 pixel resolution, which is 220 PPI: http://www.engadget.com/2012/06/11/apple-announces-next-generation-macbook-pro/.

The number of diagonal pixels (calculated by taking the square root of c^2) was then used to determine the PPI using the number of diagonal pixels divided by the diagonal size in inches. Because pixels are not always square, the calculation was performed using the Pythagorean Theorem. The diagonal method will always yield the correct PPI value. If the pixels are square, this must be known, then the calculation of PPI can be simplified: either the number of horizontal (or vertical pixels) can be divided by the width (or height) of the display in inches.

The MIL-STD-1472G Standard states that the maximal viewing distance should be used to calculate the visual angle. Hence, the viewing distance for each display was based on the upper-bound value (95th percent of the confidence intervals; this includes 95% of the population) reported in empirical previous research: 23 inches (59 cm) for the laptop display (Moffet et al., 2002) and 28 inches (71 cm) for the desktop monitor (Charness et al., 2008). Both of the cited papers empirically assessed user preferences for display viewing distances and have a combined samples size of N = 210.

One limitation is the maximal viewing distances are for a single display, not a configuration with multiple monitors. However, the above maximal viewing distances likely represent conservative values in a multiple monitor configuration because head movements should be minimized, in favor of eye movements, and sitting too close to multiple displays requires larger and more frequent head movements. Head movements should be minimized for ergonomic reasons to reduce neck strain (Nimbarte et al., 2012). Furthermore, at the present time, there is neither empirical research nor human factors recommendations for preferred viewing distance in a multiple monitor setup.

To determine the visual angle of characters and symbols, the pixel height (number of pixels) of characters and symbols were converted to height in inches:

$$I = \left(\frac{\text{Element Height in Pixels}}{\text{PPI}}\right) . \tag{5}$$

An example of how pixel heights were measured is shown in figure 2.

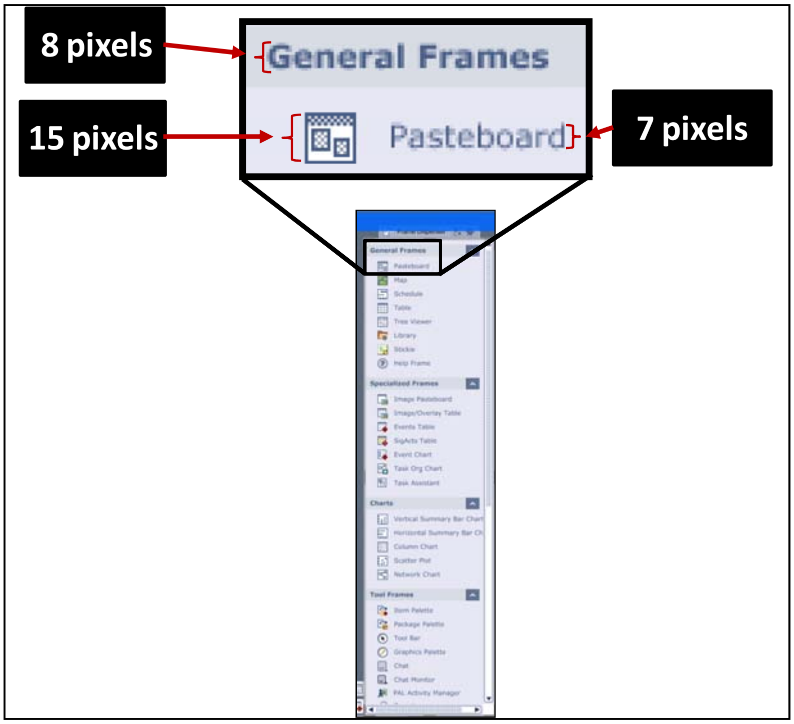

Figure 2. Example of measurement of pixel heights.

The black box on the top is zoomed in 4.5 times from the black box on the bottom. Zoomed screenshots were used to measure the pixel heights of elements in CPOF.

Last, the maximal viewing distances, listed earlier, were used to obtain the visual angle for each element using the same calculation and variables as formula 1:

$$\alpha = \tan^{-1}\left(\frac{D}{I}\right),\ \alpha = \text{visual angle},\ D = \text{viewing distance, and } I = \text{height}\ . \qquad (6)$$

3.3 MIL-STD-1472G Standard

Table 2 describes the MIL-STD-1472G requirements used in the visual evaluation of CPOF.

Table 2. Summary of MIL-STD-1472G standards for the display of visual information.

Human Factors Standard	Description	Requirement	MIL-STD-1472G Reference
1. Visual Displays	Considerations based on display specifications (physical size, resolution, brightness) and viewing distance	Various requirements, p. 108 - 110.	p. 108
2. Character and Symbol Visual Angles	1. Alphanumeric characters	Visual angle = 0.25°	p. 95
	2. Pictorial symbols	Visual angle = 0.17°	p. 95
	3. Color symbols and color characters	Visual angle = 0.33°	p. 95
	4. Isolated, color large objects	Visual angle = 0.50° minimum, 0.75° preferred	p. 95
3. Contrast and Color	Contrast for displayed information (characters and background)	6:1 contrast ratio minimum, 10:1 or greater preferred	p. 85

Note: MIL-STD-1472G Standard for visual displays: Visual angle and contrast. Note in the standard uses minutes of arc rather than degrees; 1° = 60 min of arc.

4. Results

Few of the visual elements assessed in this report met the MIL-STD-1472G Standard for visual angle: 13% of the laptop display and 32% of the desktop display met the criteria (section 4.1). Also, many visual elements (43%) had an inadequate contrast level lower (section 4.2). The impact of an inadequate visual angle, compared to the MIL-STD-1472G Standard, was reading performance 27% below the standard on the laptop display and 16% on the desktop display (section 4.3).

4.1 MIL-STD-1472G: CPOF Visual Angles

For the laptop display, only 13% (2 elements out of 16 elements evaluated) met or exceeded the minimum recommended visual angle. The desktop display was better, with 32% (5 elements out of the 16 elements evaluated) adhering to the military standard. Tables and figures are separated by the different interface boxes in CPOF. Tables 3, 4, 5, and 6 describe each element that was evaluated, its height in pixels, the military standard, and the visual angles for each type of display. The corresponding figures 3, 4, 5, and 6 show the locations of the evaluated visual elements.

The evaluated CPOF visual element, pixel height of the element, military standard for the visual angle of the type of element, and the actual visual angles for CPOF elements on the laptop and desktop displays. A visual angle in red does not meet the military standard. A visual angle in black adheres to or exceeds the military standard. All visual angles represent heights.

Table 3. CPOF menus visual angles: MIL-STD-1472G standard, laptop display, and desktop display

Element Evaluated	Height (Pixels)	MIL-STD-1472G Standard (Visual Angle)	Laptop Display (Visual Angle)	Desktop Display (Visual Angle)
Menus (Frame Dispenser, Viewer, Item Palette)				
1. Menu title	7	0.25°	**0.13°**	**0.17°**
2. Submenu titles	8	0.25°	**0.15°**	**0.19°**
3. Text (and SigActs Table variables)	8	0.25°	**0.15°**	**0.19°**
4. Icons	15	0.17°	0.28°	0.36°

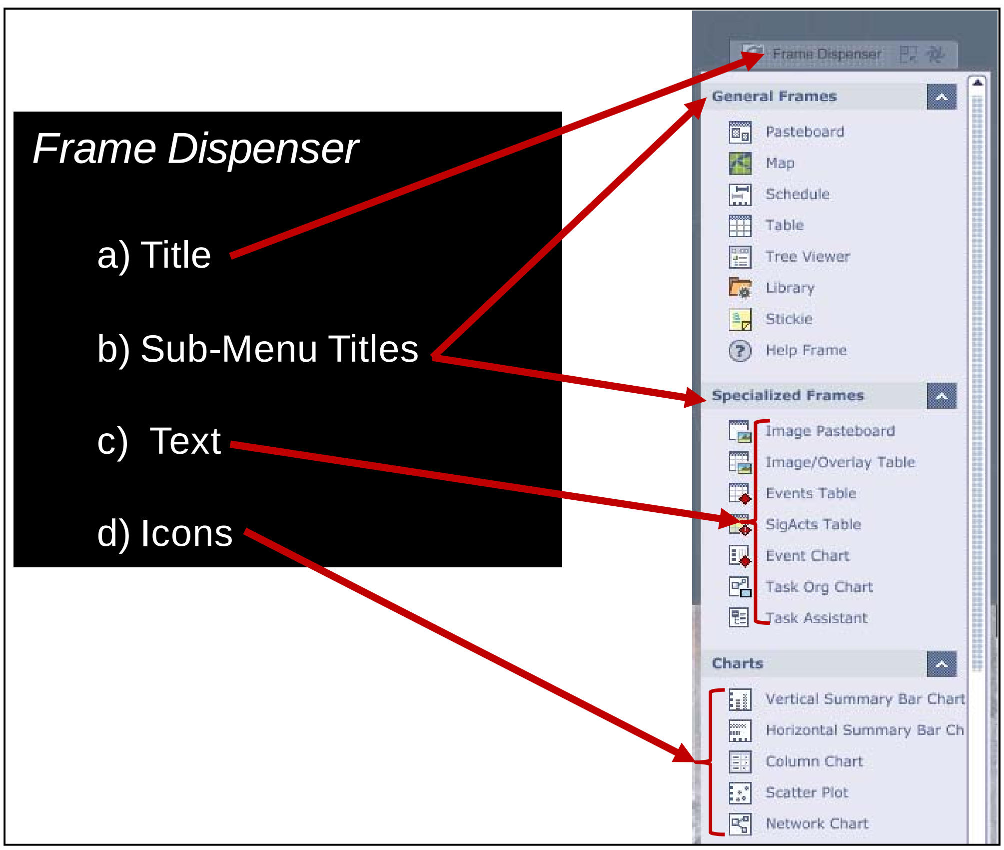

Figure 3. CPOF menus pixel heights.

Table 4. CPOF map and map controls visual angles: MIL-STD-1472G standard, laptop display, and desktop display

Element Evaluated	Height (Pixels)	MIL-STD-1472G Standard (Visual Angle)	Laptop Display (Visual Angle)	Desktop Display (Visual Angle)
1. Map				
a. Map Areas and Boundaries	16	0.25°	0.30°	0.38°
b. Unit Icon	23	0.50° minimum, 0.75° preferred	**0.43°**	**0.54°**
c. Unit Icon Name (**Bold** and CAPITALIZED)	8	0.25°	**0.15°**	**0.19°**
d. Event Icon	23	0.50° minimum, 0.75° preferred	**0.43°**	**0.54°**
e. Event Icon Name (**Bold** and CAPITALIZED)	8	0.25°	**0.15°**	**0.19°**
2. Map Controls				
a. Cardinal Directions (i.e., N, S, E, W)	7	0.25°	**0.13°**	**0.17°**
b. Coordinates (Gray text on a pale yellow background)	7	0.33°	**0.13°**	**0.17°**
c. Location/Views	6	0.25°	**0.11°**	**0.14°**

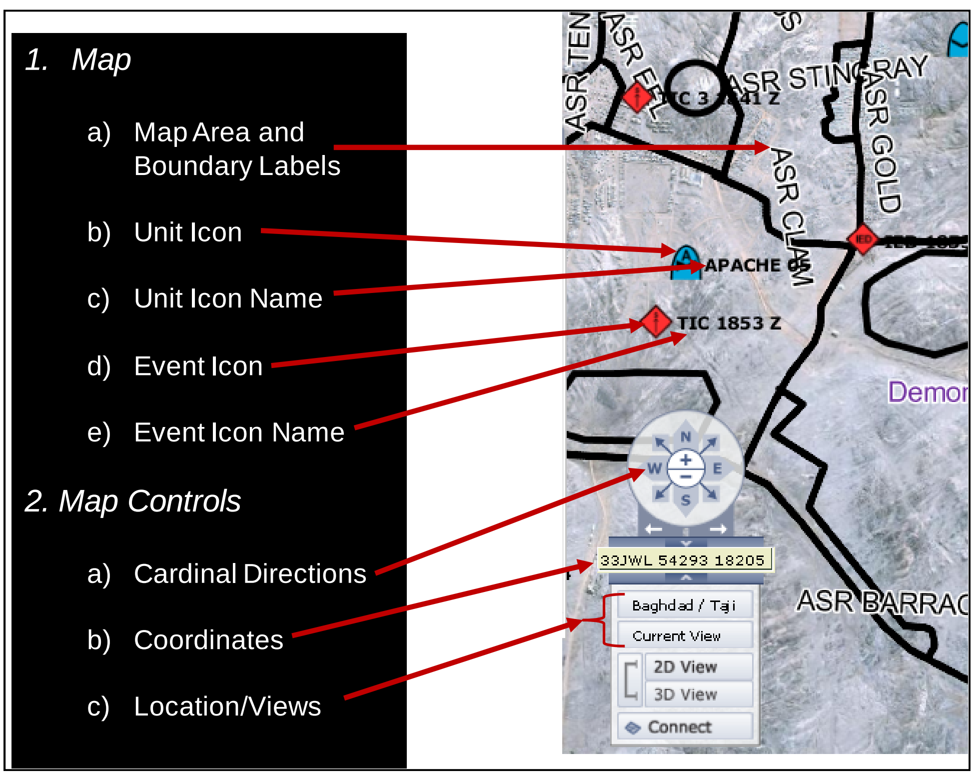

Figure 4. CPOF map and map controls pixel heights.

Table 5. CPOF Geo-Stickies: MIL-STD-1472G standard, laptop display, and desktop display.

Element Evaluated	Height (Pixels)	MIL-STD-1472G Standard (Visual Angle)	Laptop Display (Visual Angle)	Desktop Display (Visual Angle)
Geo-Stickies				
1. Title	8	0.25°	**0.15°**	**0.19°**
2. Text	11	0.25°	**0.20°**	0.26°

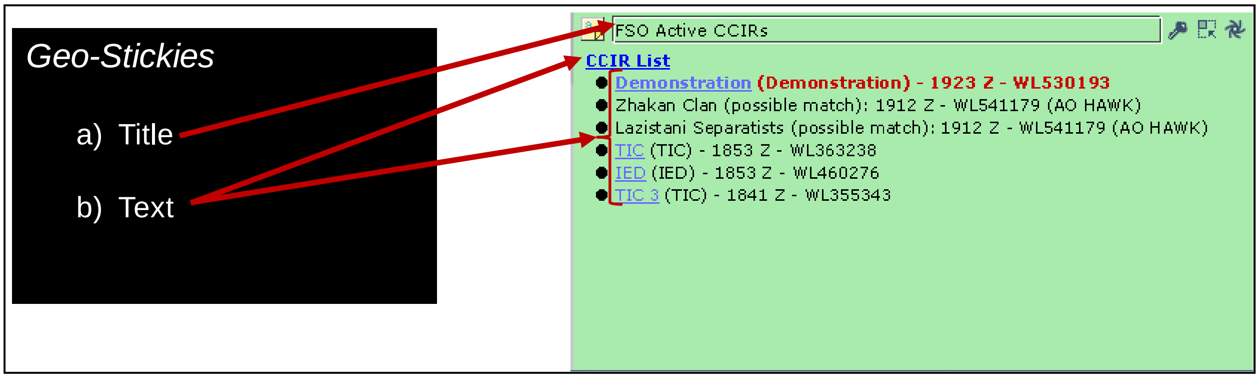

Figure 5. CPOF Geo-Stickies pixel heights.

Table 6. CPOF effort list: MIL-STD-1472G standard, laptop display, and desktop display.

Element Evaluated	Height (Pixels)	MIL-STD-1472G Standard (Visual Angle)	Laptop Display (Visual Angle)	Desktop Display (Visual Angle)
Effort List				
1. Title (**Bold**)	8	0.25°	**0.15°**	**0.19°**
2. Text Under Title (Black and orange)	8	0.25°	**0.15°**	**0.19°**

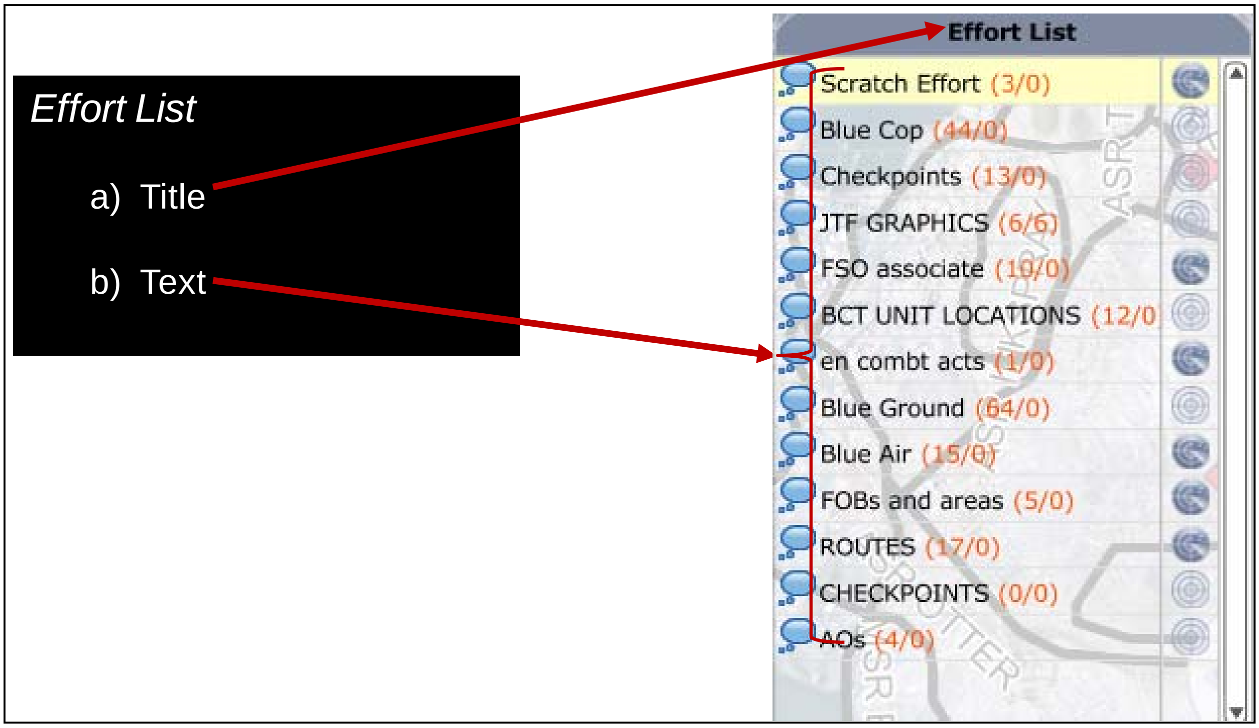

Figure 6. CPOF effort list pixel heights.

4.2 MIL-STD-1472G: CPOF Contrast

Less than half of the visual elements met the minimum contrast level: 43% (six out of 14) met the military standard (minimum 6:1 contrast ratio; preferred contrast ratio 10:1 or greater). Table 7 shows the font and the background color values and the contrast ratio based on the pixel luminance values.

Table 7. CPOF text: pixel color values and contrast ratios.

Evaluated Text	**Font: Red, Green, and Blue (RGB) Value**	**Background: Red, Green, and Blue (RGB) Value**	**Contrast Ratio**
1. Menus a. Title: Selected Not selected	 84, 88, 95 94, 102, 114	 183, 191, 208 Depends on background	 **3.9 : 1** --
b. Submenu titles	109, 125, 158	216, 220, 228	**3.0 : 1**
c. Text under titles	117, 132, 166	231, 231, 244	**3.1 : 1**
d. SigActs table (variables)	79, 106, 79	123, 157, 123	**2.0 : 1**
2. Map Controls			
a. Cardinal directions (N, S, E, W)	145, 157, 183	189, 196, 211	**1.6 : 1**
b. Cardinal direction button	189, 196, 211	Depends on map background	--
c. Coordinates	128, 128, 128	237, 238, 200	**3.3 : 1**
d. Location/Views: Button selected	0, 0, 0 (black)	239, 241, 245	18.6 : 1
Button not selected	127, 127, 130	239, 241, 245	**3.5 : 1**
3. Geo-Stickies			
Text Pink background Yellow background Green background	0, 0, 0 (black)	 252, 207, 216 255, 255, 157 168, 235, 173	 15.1 : 1 20.0 : 1 15.2 : 1
4. Effort List			
a. Title	0, 0, 0 (black)	129, 139, 162	6.1 : 1
b. Efforts in list: Text (selected) Numbers (selected)	 24, 24, 19 254, 117, 43	 252, 253, 197 252, 253, 197	 17.0 :1 **2.6 : 1**

Note: The evaluated visual element, character RGB values, background RGB values, and the character and background contrast ratio. Contrast ratios in red do not conform to the military standard.

Two contrast values could not be calculated because the background was semi-transparent, thus it varied depending on the background map.

4.3 Reading Performance

Reading performance in CPOF is estimated to be below the military standard by 27% for the laptop display, 16% for the desktop display, and for both displays an average of 22% below (see figure 7). Reading performance was estimated to be impaired to these levels because few elements in CPOF subtended a visual angle that met the military standard. The impact of visual angle on cognitive performance was calculated for reading text using the visual angle recommended in the military standard for text as the baseline value. Using the visual angles of characters, predicted reading performance was calculated using the psychophysical function of reading performance from Legge et al. (1985). There are several pertinent details regarding how Legge et al. (1985) measured reading.

In Legge et al. (1985), reading was assessed at its maximal possible rate using fast scrolling text, a method called rapid serial visual presentation (RSVP). This presentation method requires speed reading. Legge et al. (1985) used short sentences with RSVP, rapidly scrolling text consisting of two to three words presented simultaneously. In CPOF, static, nonmoving text is read and it generally consists of a few words rather than an entire sentence. Also, in Legge et al. (1985), reading performance was adjusted for error (e.g., if the reading speed was 200 words per minute, but in that minute 40 words were incorrect, the effective reading speed was calculated to be 160 words per minute). Additionally, all participants had normal or corrected-to-normal vision (i.e., 20/20 vision).

Using the military standard for text visual angle, reading speed using the psychophysical function in Legge et al. (1985) was predicted to be 209 words per minute. This was used to establish baseline performance. The average text visual angles in CPOF were as follows:

1. Laptop display: 0.16°
2. Desktop display: 0.21°

Using the above visual angles for the laptop and desktop displays, and the corresponding maximal viewing distance, reading speed is estimated to be 152 words per minute and 176 words per minute, respectively, using the psychophysical function. Figure 7 shows the impact of visual angle on reading performance.

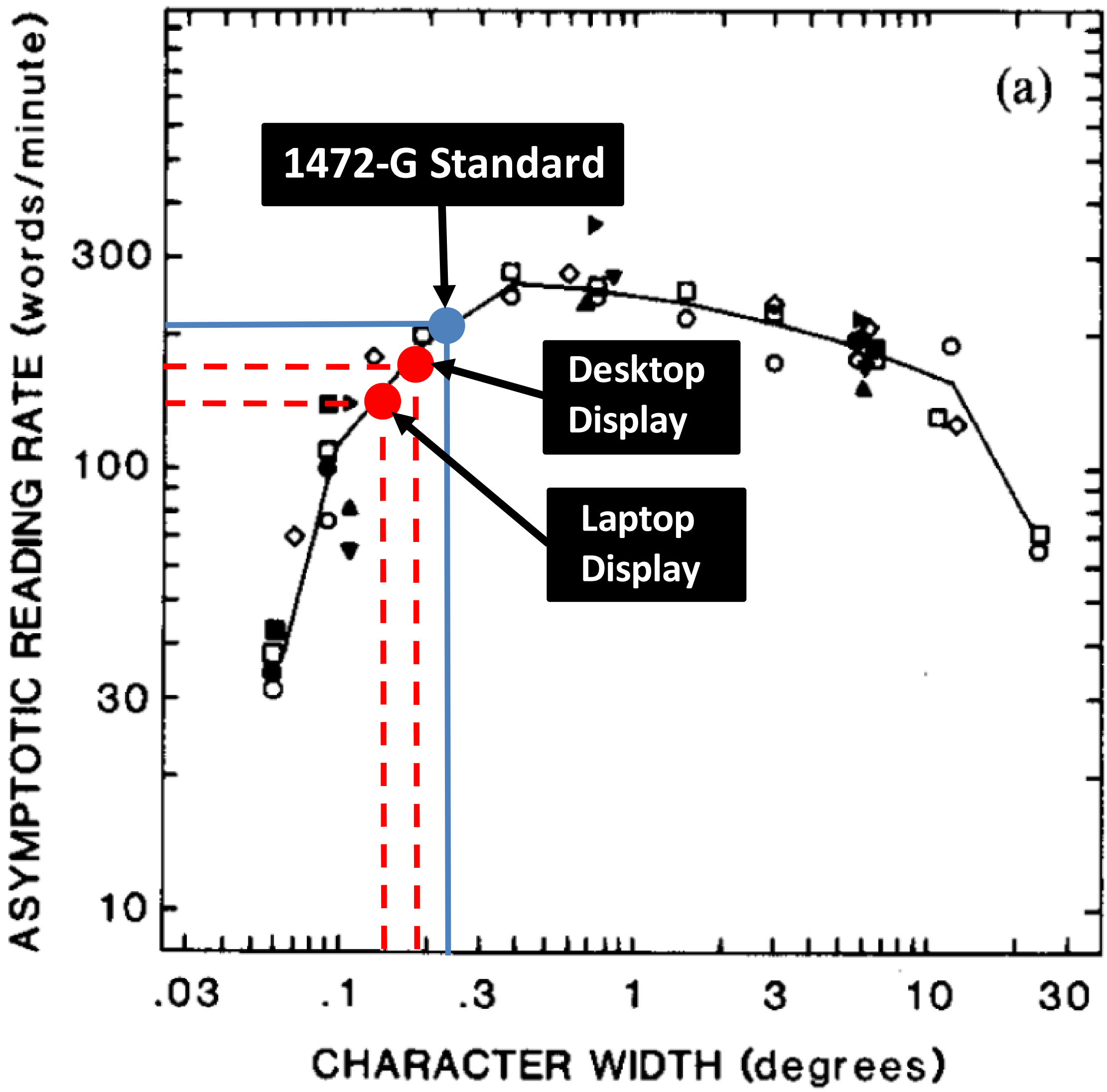

Figure 7. CPOF visual angle and reading performance: MIL-STD-1472G standard, laptop display, and desktop display.

Figure 7 is from Legge et al. (1985), figure 6a, p. 247, with modifications. The vertical axis is reading performance (reading speed adjusted for error) and the horizontal axis is the visual angle of character width in degrees. The modifications are the following: solid blue lines and the blue dot, indicating military standard for text visual angle and the corresponding reading speed, and red dashed lines and red dots, depicting the text visual angle for the two types of visual displays used with CPOF and the corresponding reading speeds.*

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* The black and white symbols can be ignored because they do not have a meaningful impact on performance. Symbols represent different presentations of stimuli: black text on a white background and white text on a black background, and different measures of reading performance: reading aloud versus reading silently.

4.3.1 Limitations and Assumptions

There are key limitations and assumptions in the calculation of reading performance. First, optimal display characteristics (brightness, contrast, and color) and ambient lighting were assumed. Hence, these factors were considered optimal for reading performance. Second, there are differences between the methodology used in Legge et al. (1985) and how information is presented in CPOF.

Legge et al. (1985) is based on optimal stimuli because the characters were at the highest possible contrast (black text on a white background or vice-versa). A little over half of the evaluated CPOF visual elements CPOF had a contrast level reaching the military standard. The calculations of reading performance ignore contrast. For visual angles less than 0.30°, an inadequate contrast level clearly decreases reading performance (Legge et al., 1987). The relationship between visual angle and contrast is non-linear with a large problem space, that is, many possible values for each (Legge et al., 1987). Unfortunately, this makes it difficult to determine the combined negative impact on reading performance for insufficient visual angles and inadequate contrast.

Another important difference is that Legge et al. (1985) presented short sentences, albeit two to three words at a time using RSVP. Whereas the information read in CPOF is generally limited to a few words at a time. There are differences in reading performance for RSVP versus static text, with higher performance for the former. However, RSVP has advantages for experimental control and measurement and generalizes to normal, real-world reading (Legge et al., 1985). It is important to note that although this is a potential confound, it is a constant applied equally to all performance estimates. Reading performance is comparable whether statically presented text is shown as either an entire sentence or a single word (e.g., Fischler and Bloom, 1980). Although consistent with MIL-1472-G standard, an additional limitation is that the calculation of viewing distance is based on the maximum possible values.

The last limitation of this report is that cognitive performance was not directly measured in a laboratory-based experiment with CPOF. Instead, it was based on earlier research establishing the functional relationship between reading speed and visual angle (Legge et al., 1985). Despite this limitation, Legge et al. (1985) used an objective cognitive performance measure (reading speed) to precisely quantify the relationship between character visual angle and reading speed for individuals with normal vision. Limitations aside, the estimated reading performance with CPOF clearly demonstrates negative outcomes for the lack of adherence to MIL-1472-G.

5. Recommendations

Because many elements in the visual information display of CPOF do not meet the military standard, the following is recommended.

5.1 Increase the Visual Angle

Implement support in CPOF to change the size of all visual elements, including the font size, to at least 0.25° for characters. Ideally, the scaling of visual elements could be independently specified for by monitor using the pixels per inch of each display device.

CPOF does not support scaling using the display settings in Microsoft Windows, see the following guidelines ("Writing High-DPI Win32 Applications," n.d.). Anecdotally, few programs support this feature in Windows. Nevertheless, CPOF is a safety critical system and not a consumer application.

Thus, there is currently no good method for increasing the visual angle of elements in CPOF. Furthermore, the visual angle of elements will shrink in the future as the pixel density of displays increases. To optimize cognitive performance it is recommended that CPOF supports Windows Scaling or, alternatively, has a setting to change the size of all visual elements, not just the font size. Either would achieve the same result, a larger visual angle. Ideally, the size of visual elements in CPOF could be specified separately for each display type. The two types of monitors have different specifications in terms of pixels per inch (resolution and size) and viewing distance. Thus, a single scaling or size setting may not be optimal for the laptop and desktop displays simultaneously.

5.1.1 Suboptimal Methods for Increasing the Visual Angle

There are several obvious methods for increasing the visual angle, none of which require any changes to CPOF unlike the above recommendation. Nevertheless, all of these methods are suboptimal because they solve one problem while creating other problems:

1. *Decrease Viewing Distance:* Sitting closer to the displays is an obvious way to increase the visual angles of characters and symbols. However, there are obvious ergonomic considerations; eye strain is more prevalent at closer viewing distances and more head movements are required in a multi-monitor setup. Head movements should be minimized. Furthermore, because the standard configuration for CPOF is three or four displays, sitting closer to the displays may increase eye-strain and neck-strain and decrease the field of view, limited the visibility of information on other displays. Leaning in to read information is a work around for the same reasons.

2. *Lower the Display Resolution:* This would increase the size of visual elements. The trade-off of using display at a non-native resolution is reduced sharpness and, of course, less information on the display due to a lower spatial resolution. In addition, if the lower resolution is not linearly scaled (i.e., the same aspect ratio is maintained) from the native resolution, then visual elements will be distorted by stretching or squishing.

3. *Manually Resize Boxes:* Some boxes in CPOF can be resized, which also increases the size of many of the visual elements in the box. This method is limited to certain boxes and map elements, for example map controls cannot be resized. In addition, this must be done manually by dragging the lower right corner of the box (this defies the convention in Microsoft Windows in which performing this action increases the size of a window without zooming in).

5.2 Increase Contrast

Changes to characters and backgrounds are necessary so that all reach a minimum contrast level of 6:1. High contrast can be created with dark characters on a light background or light characters on a dark background.

The main cause for the suboptimal contrast ratios are dark background colors. High contrast can be achieved with either dark elements on a light background or light elements on a dark background. Most of the characters used dark colors (black or dark gray), but the backgrounds were not necessarily light (e.g., dark green, gray). To increase contrast, color changes to the background and/or the text are required. The estimates of reading performance do not reflect the inadequate contrast levels, thus they are likely to be underestimates given the detrimental effects the combination that a small visual angle and low contrast have on reading performance (Legge et al., 1987).

6. Conclusions

High performance from technical systems is necessary for achieving the payoffs envisioned by the Army transformation to network-enabled operations. The four tenets of network-enabled operations cannot be sufficiently realized unless cognitive performance, such as reading, is well-supported by the information systems. Prior research on CPOF has primarily focused on properties of technical systems, rather than human use. Although the technical performance and capabilities of an MCS are necessary to achieving information superiority, the systems must also meet Soldier capabilities and needs. Both are needed to realize the advantages of information superiority and effective mission command. In an information rich environment, the ability to process the information quickly, narrowly defined here as reading speed, is required for information superiority.

The findings here suggest that reading performance with the CPOF display may involve more controlled processing rather than automatic processing. Reading is typically an automatic process, but with impoverished visual information there is less dependence on perception and more reliance memory, attention, and decision-making. Controlled processing is more error prone than automatic processing (Shiffrin and Schneider, 1977).

A wide-range of human factors research emphasizes that, generally, visual information should be processed automatically to support human performance (Norman, 2002; Shneiderman, 2003; Wickens et al., 1998). Higher level cognitive resources are best preserved for higher ordered sense-making tasks, such as understanding of future threats, proactive decision-making with respect to capabilities, and expression and comprehension of command intent. The incident with USS Vincennes demonstrates why the visual display of information in technical systems must generally support automatic processing of visual information. Furthermore, the example with improved medication labels indicates that fairly simple changes to a visual display (larger fonts, simplified language, etc) leads to better human information processing.

Assuming the user will lean in to read information or use other work-arounds cannot fully compensate for a poorly designed visual display. First, it cannot be assumed work-arounds will be used, for example sitting closer to the visual display. Second, even if workarounds are used there is a possibility of unintended side-effects, for example eye strain and decreased field of view.

The present visual display of CPOF does not meet the military standard in terms of visual angle and contrast. Furthermore, this report shows why adherence to the military standard is essential to cognitive task performance. Compared to the military standard, reading performance in CPOF was estimated to be on average 22% lower for both display types. Although the cognitive performance evaluation was limited to text, the visual angle for all elements, such as symbols, were compared to the requirements in the military standard. Furthermore, the evaluation of reading performance did not include the issues with low contrast.

Last, the use of objective measures of cognitive performance is fundamental in safety critical systems (Andre and Wickens, 1995). An MCS is not a consumer product; a domain in which user preferences and beliefs tend to be given great weight. The use of an objective measure of cognitive performance, reading, combined with the non-adherence to aspects of the military standard indicate there are visual deficiencies in CPOF.

6.1 Future Research

Future research on MCSs should strive to quantify and optimize objective cognitive performance. For example, objective cognitive performance for different interfaces in MCSs can be empirically measured and compared using the timing and error rates to perform common tasks such as creating an event for a potential improvised explosive device (IED). In addition, different prototypes of system interfaces should be subject to behavioral assessment in order to refine the display configuration to achieve optimal performance by improving the integration of what is essentially a Soldier system. Experimental scenarios can be used to simulate incoming and outgoing information in the context of mission command and evaluate performance across a variety of mission command tasks.

The above paradigm can also be applied to the CPOF, which has an unusual interface that does not follow Microsoft Windows conventions (Middlebrooks, 2008). However, the CPOF interface has not been thoroughly evaluated, especially an objective assessment. Anecdotal evidence on the usability of CPOF is mixed. Nevertheless, CPOF training costs indicate that learning to use the interface is a challenge. Modifications to the CPOF interface may lead to improved cognitive performance, extending beyond perception, and could have further benefits: better Soldier understanding and use of capabilities in CPOF. Comparisons and testing of different interfaces can also be informed by models of expert human performance of tasks using GOMS. CogTool is an application that provides GOMS predictive modeling: http://cogtool.hcii.cs.cmu.edu/

Finally, technological capabilities that can infer Soldier goals and needs, such as proactive software agent or associate technologies, have the potential to improve the presentation of information and ease of use of MCSs, increasing cognitive performance and, thus, mission effectiveness (e.g., an associate system for decision support and objective measurement of cognitive performance; Buchler et al., 2013) . Such tools may also be effective technology for improving training. The U.S. Army will spend millions of dollars to support CPOF training, and this software system also requires a heavy contractor footprint both in theater and at home station. Even modest improvements in the usability of a system can dramatically reduce training cost, both as an initial investment (reduced training time) and a recurring one (better retention), in addition to better cognitive performance.

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List of Symbols, Abbreviations, and Acronyms

CPOF	Command Post of the Future
GOMS	goals, operators, methods, and selection
IED	improvised explosive device
MANPRINT	Manpower and Personnel Integration
MCS	Mission Command System
PPI	pixels per inch
RSVP	rapid serial visual presentation

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